Optimizing TBM Selection For Risk Mitigation

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Tunneling Short Course
Boulder Colorado September 12-15th
Why Understand and Manage Risk?

– Managing risk is how we make projects successful
– Risks always exist
– Outcome when risk is ignored
  • Claims
  • Underachieving projects
  • Lawsuits
  • Reduced safety
Risk Management Process

Risk management and impact versus time (Caiden 2008)
How Do We Manage Risk?

- Identify and assess risks
  - Third-Party
  - Financial / Contractual
  - Technical
- Analysis - determine who is best able to manage the identified risk
- Identification, assessment and management of risks are ongoing processes

Tunneling Risks / Risk Management

AECOM’s Risk Management Process

- Identify Risks
- Establish Likelihood & Consequence
- Establish Mitigation Plans & Ownership
- Rank Risks
- Manage Risks

- Mitigate
- Share
- Allocate/Transfer
- Status
- Reset priorities
Third-Party Risks

- Disruption to residents and loss of public amenity
- Disruption to business / commerce
- ROW issues
- MOT / Disruption to traffic increased accidents
- Disruption to adjacent utilities
- Environmental impacts
Contractual / Financial Risks

- Risk of performance
- Penalties for failure to meet deadlines
- Unlimited liability for failures or problems
- Unpredictable consequential damages
- Extended guarantees or warranties
Key Tunneling Risks – Technical

- Insufficient geological information
- Settlement and damage to structures
- Gassy tunneling conditions
- Groundwater inflows
- Mixed-face tunneling conditions
- Choice of primary lining
- Spoil disposal
- Inexperienced personnel
- Incorrect means and methods
- Inadequate equipment
Risk Allocation Tools

- Method of Procurement
- Geotechnical data report
- Geotechnical baseline report

- Differing site conditions (DSR) clause
- Environmental baseline reports
- Risk register
- Escrow bid documents
- Dispute review boards
- Field monitoring program
- Pre-construction survey
- Specify defined obstructions
Procurement Method For Tunneling projects

- **Base Project Cost**
  - **Contractor's Contingency & Margin**
  - **Owner's Contingency**

- **Construction Time**
  - **Design/Build**
  - **GC/CM**
  - **D/B/B**

- **Owners Financial Risk**
  - **Contractors Financial Risk**
Geotechnical Information – Underground Construction

– Without Geotechnical information – Choosing means and methods for a tunnel project is like - *driving in the dark without lights*

– All project delivery methods will gain with lower risk for the contractor & client = Lower prices, if a GBR or at least a GDR are provided at the time of bid.
Tunnel Excavation Methods

- Conventional
  - Drill and Blast (D&B)
  - Mechanized excavation / Road headers etc.

- Mechanized
  - Open TBM – Gripper & Open shielded
  - Closed TBM – Slurry, EPB & Dual mode/ Hybrid

- Specialty
  - Microtunneling
  - Immersed Tube
  - Cut and Cover
- Conventional Tunneling
  - None - Rock (Bolts)
  - NATM/SEM – Bolts, Ring Beam / Lattice Girder, Mesh & Shotcrete
  - Precast pipes
  - Cast in Situ RC - Formwork

- Mechanized Tunneling
  - None - Rock (Bolts)
  - Rapid Liner - Bolts, Ring Beam / Lattice Girder, Mesh & Shotcrete
  - Pre Cast Pipes
  - Tunnel Pre Cast Rings / Segments
Tunnel Method Choice - Rock

– Dry Rock or Very Low Permeability – (No Blasting)
  • TBM – Open Gripper type, Open Shielded
  • Road Header - <60mpa
  • Drill & Chemical splitting (Short Lengths)

– Primary Support
  • Not Required to Rock Bolts
  • Wire Mesh / Ring Beams / Lagging / Sprayed Concrete
  • Pre Cast Segment Liner Rings (Primary & Final Liner)

– Final Liner
  • None – Bare rock walls
  • Cast In Situ RC Liner

In rock with high water table and low permeability there is always a danger of high water flows from fractured zones
Unshielded Open Rock TBM – Massive Rock

Gripper Open Cutter
For massive rock

Gripper Shield with Plated Face Support
For fractured – Blocky rock face, back mounted cutters
Shielded Open Rock TBM – Fractured Rock

Double Shield Gripper Rock TBM

Single Shield Gripper Rock TBM
Method Choice – Rock & Variable ground - Water

- Rock & Interbedded or zones of Soft Ground – Water High Permeability
  - Closed Face Shielded TBM – EPB and Slurry

- Primary / Final Support
  - Pre Cast RC tunnel lining

- Options for Short tunnels / Cross Passages
  - Ground treatment ahead of excavation (De watering, Grouting)
    o SEM - Sprayed Concrete / mesh / Bolts - Primary Liner
    o Cast in Situ Final liner
Closed Face shielded Rock / Mixed Face TBM

Typically No Grippers

Slurry and EPB TBM’s
Method Choice

– Soft Ground – Dry (Urban, Non Urban)
  • Short Drives – Consolidated Ground (Clay, Silt)
    • Shielded Back Hoe type Excavator
    • NATM Primary support (Shotcrete, mesh, Lattice Girders)
    • Cast in Situ Final Liner
    • Fore poling and grouting may be required

  • Long Drives
    • TBM – EPB - Shielded, Open or Closed
    • Liner- Pre Cast Segmental Rings

• Small Dia. <3m
  • Pipe Jacking – Open face shield / EPB
  • Hand Mine or mechanical excavation
  • Pre Cast Jacking Pipes
Method Choice

- Soft Ground – Wet – Unstable High Permeability (Sand, Silt)
  
  • TBM – Shielded – Closed Face  
    – Slurry (EPB - Clay)  
    • Liner Pre Cast Segmental Tunnel Rings

• Small Dia. <3m  
  • Microtunnelling – Slurry / EPB  
  • Pre Cast Pipes  
    – RC – Reinforced Concrete  
    – PC - Polymer Concrete  
    – VC - Vitrified Clay  
    – GFRP -Composite - Fiberglass
Earth Pressure Balance - TBM

Auger and belt conveyor
Earth Pressure Balance (EPB) - TBM

Foam additions in unconsolidated ground
Slurry TBM

Slurry System
Solids Removal
Slurry TBM
Slurry TBM

- Cohesive Material
  - Low fat clays & silts
  - Slurry mode with chamber pressure jets

- Granular Material
  - Sands & gravels
  - Slurry mix shield mode with air pressure chamber

- Rock
  - Slurry mode with medium jets
  - Invert jet
Traditional EPB v Slurry TBM

Particle Size Distribution

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Clay</th>
<th>Fine</th>
<th>Medium</th>
<th>Coarse</th>
<th>Sand</th>
<th>Fine</th>
<th>Medium</th>
<th>Coarse</th>
<th>Gravel</th>
<th>Fine</th>
<th>Medium</th>
<th>Coarse</th>
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<tbody>
<tr>
<td>Silt</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td>100</td>
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<td>70</td>
<td>60</td>
<td>50</td>
<td>40</td>
<td>30</td>
<td>20</td>
<td>10</td>
<td>0</td>
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Grain diameter d (mm)

EPB

Slurry
Extended Scope of EPB & Slurry TBM’s
Method Choice – Variable Ground

– Ground changes along the alignment from massive rock with low permeability to wet alluvium

– From stiff clay to running granular soils with high permeability and ground water pressures

– TBM Options - Hybrid, Multi Mode or Dual Mode TBM’s
  - Dual Mode –
    - Open & Closed EPB
    - Closed EPB & Slurry
  - Multi Mode TBM
    - Open, Closed EPB & Slurry
Dual Mode TBM:
• Open Rock and Closed EPB
• Closed Slurry / EPB
Dual Mode EPB/Slurry TBM

- Slurry / EPB Auger system with slurry spoil removal – No belt Conveyor or muck skips required
- May be switched from EPB with Slurrification to full slurry operation in the ground in a matter of hours
Multi Mode TBM

EPB mode with Slurry mix shield air pressure chamber

Air Pressure Chamber

Slurrification Chamber
Risk & Hindsight – Pinglin (Hsuehshan) Tunnels - Taiwan

- Twin road tunnels 8 miles long and 39ft diameter and a pilot tunnel of 16ft
  Started in 1991 due for completion 1999 actual completion 2006

- Complex Geology of
  - Sandstone and quartzite's up to UCS of 25,000psi
  - 6 major fault zones and 98 shear zones with very poor rock conditions
  - High pressure (285 psi) water inflows reaching 400gal/sec
  - Up to 2500ft overburden
Pinglin (Hsuehshan) Tunnels - Taiwan

- Open rock single shield TBM - 39ft
  - Fully plated Cutter
  - High torque (x1.65) to similar diameter TBM’s
  - Adjustable overcut of up to 2.5in to handle ground squeezing
  - RC segmental liner rings for primary support

- TBM’s became stuck on numerous occasions due to rock collapse and extensive water flows delaying construction

- Revert to Drill & Blast for long sections of the tunnels with rock falls and inundation

- One TBM was abandoned in the ground

- 25 Worker deaths during construction
Risk & Hindsight – Arrowhead Tunnels - California

- 3 major tunnels to supply water to Diamond Valley Reservoir – originally due for completion in 2003 was completed 2009

- Work started in 1999 but was stopped due to very high water flows the TBM in use was and open gripper machine with un-gasketed steel segment primary support

- The ground varied from hard massive granite (36,000psi) to fractured crushed rock and squeezing raveling ground with several fault zones with high volume high pressure (150psi) water flows
The project east (22,000ft) and west (20,000ft) tunnels were redesigned and re bid 2002 with work starting in 2003

- 2 x 19ft closed face hard rock TBM’s
- Open screw conveyor system and installing
- RC segmental liner rings
- TBM’s were equipped with extensive drilling and grouting facilities - 15 shield and face openings

The TBM’s were modified after a time in the ground

- Increased Torque
- Increased thrust
- Installation of a water circulation system with separation plant to remove fines (an early slurrification system)
- EPB style foam and conditioning system.
- 19 additional face grouting drill ports were added and were the most important aspect for the eventual success of the tunneling
Arrowhead Tunnels - California

- TBM Modifications

<table>
<thead>
<tr>
<th>Description</th>
<th>Original TBM Design</th>
<th>Modified TBM Design</th>
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<tbody>
<tr>
<td>Cutterhead operational torque</td>
<td>2,000 kNm</td>
<td>3,520 kNm</td>
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<tr>
<td></td>
<td>1.5 million ft-lbs</td>
<td>2.6 million ft-lbs</td>
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<tr>
<td>Cutterhead exceptional torque</td>
<td>2,323 kNm</td>
<td>4,400 kNm</td>
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<tr>
<td></td>
<td>1.7 million ft-lbs</td>
<td>3.3 million ft-lbs</td>
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<tr>
<td>Cutterhead speed (max)</td>
<td>9.75 rpm</td>
<td>7.5 rpm</td>
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<tr>
<td>Cutterhead rear annular gap</td>
<td>100 mm</td>
<td>75 mm</td>
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<tr>
<td></td>
<td>4 inches</td>
<td>3 inches</td>
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<tr>
<td>Shield thrust</td>
<td>29,270 kN</td>
<td>58,540 kN</td>
</tr>
<tr>
<td></td>
<td>3,300 tons</td>
<td>6,600 tons</td>
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<tr>
<td>Probe drilling holes</td>
<td>26 each (1.5° and 8° lookout angle)</td>
<td>45 each (1.5°, 4° and 8° look-out)</td>
</tr>
<tr>
<td>Probe drills</td>
<td>4 each; 1 front, 1 erector, 2 rear</td>
<td>5 each; 2 front, 1 erector, 2 rear</td>
</tr>
<tr>
<td>Screw auger</td>
<td>13.35 m (44 ft) single piece unit</td>
<td>4-piece (3.35 m each piece)</td>
</tr>
<tr>
<td>EPBM capabilities</td>
<td>None</td>
<td>Sensors, mixing arms, foam mixer</td>
</tr>
<tr>
<td>Slurry handling/separation system</td>
<td>None</td>
<td>54 l/sec (850 gpm) maximum</td>
</tr>
</tbody>
</table>
Lake Mead Intake N0 3 – Dual Mode Open & Slurry

- Mixed Ground conditions – Rock, conglomerate breccia, fault zones
- 220psi (15 Bar) water pressure – Highest tunnel water pressure in the World
- Design Build Contract

- Client completed 50 bore holes to identify a corridor alignment and to provide a GDR for the bid.
- Dual Mode TBM – Slurry/Open with special seals for high external pressures
Port of Miami – 42Ft Multi Mode EPB / Slurry TBM

- Variable ground conditions with high permeability limestone and karst formation
- Water pressure up to 47psi (3bar)
- PPP Contract with special financial contingency arrangements with the client

- Special Multi Mode EPB/Slurry TBM
  - EPB with screw Conveyor
  - Slurry circuit with stone crusher
  - Slurrification box
  - Probing and grouting
Tuen Mun CLKL – Hong Kong Dual Sized EPB TBM

- Long 6 mile undersea crossing 57.7ft (World's Largest) Slurry TBM
- Maximum 70psi (5Bar) water head
- Little Geotechnical information- forecast to be Alluvium with weathered granite, possibility of strong granite
- DB Contract with TBM specified and special pay conditions based on ground conditions
- Dual Sized Slurry TBM 57.7ft and reduced to 46ft
- Robotic cutter inspection and replacement over 60% of face
- Hyperbaric interventions
Real Time Cutter & Geotechnical Monitoring

Disc Cutters

- Cutter head with 16 heavy duty disc cutters successfully used in difficult cutting areas.
- Disc cutter quality and design approved by project after project since 1985.
- Mobydisc electronic circuit is incorporated into the disc cutter.
- The circuit provides energy to the sensors and transmits data to the TBM control cabin.
- Mounting of Mobydisc disc cutter is similar to a standard disc.

CONVENTIONAL MIXED GROUND HEAVY DUTY CUTTER HEAD WITH 16 HEAVY DUTY DISC CUTTERS WITH CUTTER WEAR AND GEOTECHNICAL MONITORING CAPABILITY

REAL TIME INFORMATION ROUTE

Mobydisc disc cutters send real-time information from the disc cutters under 8 bar to the TBM control cabin.

MOBYDIC IS THE ONLY FUNCTIONALLY PROVEN REAL TIME CUTTERHEAD AND GEOTECHNICAL MONITORING SYSTEM IN THE WORLD WITH A SUCCESSFUL HONG KONG HISTORY IN FULL AND MIXED HYDROBAC SLURRY CONDITIONS.

REAL TIME GEOLOGICAL MAPPING IN TBM CONTROL CABIN

- Disc cutter is 3D.
- Rotation: Temperature: 1°C.
- Radial force: 18 kN/mm.
- After calibration, the load applied during excavation on each disc cutter is represented by a color gradient.
- Red color represents an increase in load over design.

OPTIMISATION OF EXCAVATING PARAMETERS

- In the TBM control cabin, Mobydisc software will help to present efficiently all the information concerning the condition of the disc cutter to the TBM shift boss & pilot.
- The visual representation of the disc cutter load will help them to adjust and optimize the TBM excavating parameters in real time.

DISC CUTTER WEAR MEASUREMENT

- When disc cutter steel is worn, its radioactivity is reduced, so the rotation speed of the disc cutter correlates to the cutter head condition, determining the amount of wear.
- If a disc cutter stops rotating, it emits an alarm, indicating it is time to replace the disc cutter.

AECOM
Cutter Changing Robot
TBM Hyperbaric Intervention

4 x 2 saturated divers from Dec 2015 to Jul 2016 @4/5 bars
- 6 Doctors
- 3 Nurse (Day / Night)
- 45 Professional Divers
- 12 live support technicians
Tunnel Cross Passages

56 Cross Passages (100m spacing - 328ft) with 44 by Slurry Pipe Jacking
Summary

– In Rock Open Gripper TBM’s give the highest performance for excavation – Are susceptible to unanticipated ground changes including fault zones and water flows

– Rock open TBM’s should have extensive probing and grouting capability

– Uncertainty in the ground conditions increases risk of delay and higher costs

– Use of Closed Shielded TBM’s with RC bolted and gasketed segmental liner rings reduces risk but increases cost due to slower production and higher cost of the equipment.

– Hybrid / Multi Mode TBM’s with robotics and ground sensing equipment is a reality for variable & mixed ground conditions
Research and Development

– NeTTUN financed by an EU grant is carrying out research on improving TBM’s and tunnel related issues

– Ground Prediction systems from the TBM cutter face:
  • Electromagnetic Radar – On Trial on the Turin rail tunnel 2016
  • Seismic source and sensors – Undergoing Lab trials
  • Software development to combine information to predict ground conditions ahead of the excavation face.

– Robotics for Cutter disc inspection and replacement
  • Robots in use for cutter inspection
  • Robots developed and used on the Tuen Mun – HK TBM replace cutter over 60% of the outer diameter of the TBM

– Improvement of design and materials for drag bits
  • New improved steel compounds developed – Field testing
  • New efficient designs developed to minimize wear maximize penetration
Thank You